Prospects for strangeness and heavy flavor physics at FAIR

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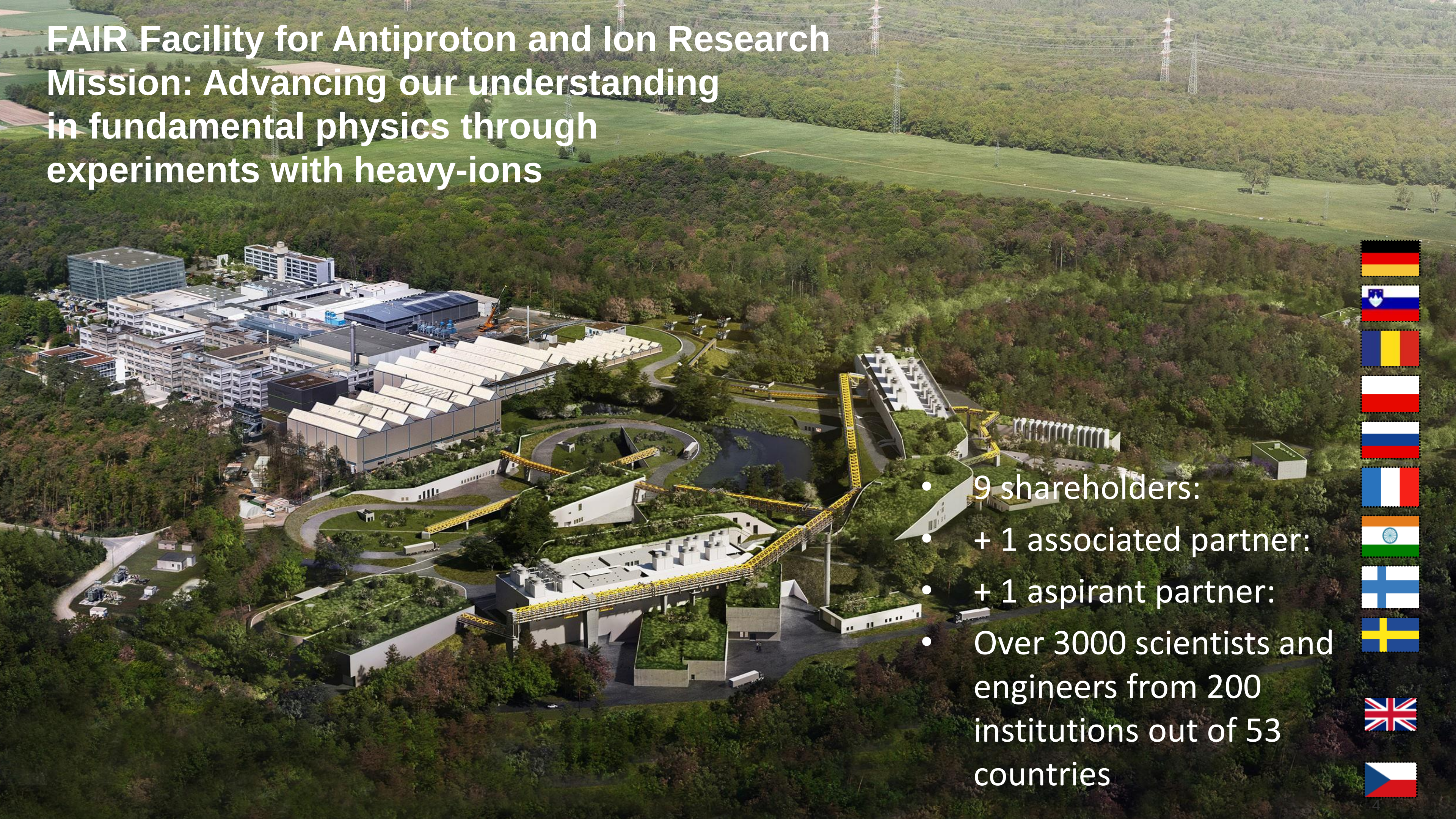
FAIR Facility for Antiproton and Ion Research

Overview

- Introduction to FAIR
- Physics perspectives at FAIR
- Strangeness at FAIR
- Charm at FAIR
- Summary

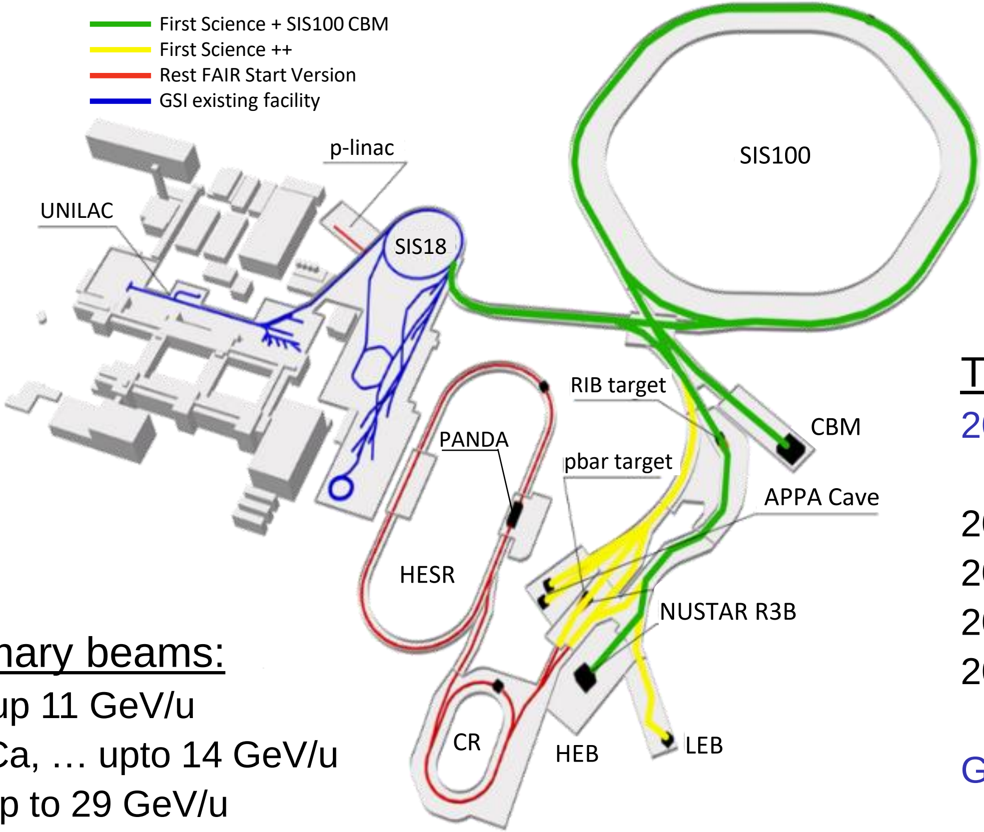
FAIR Facility for Antiproton and Ion Research
Mission: Advancing our understanding
in fundamental physics through
experiments with heavy ions



FAIR Facility for Antiproton and Ion Research
Mission: Advancing our understanding in fundamental physics through experiments with heavy-ions

- 9 shareholders:
- + 1 associated partner:
- + 1 aspirant partner:
- Over 3000 scientists and engineers from 200 institutions out of 53 countries

FAIR Accelerator Facilities



Timeline

2018 start of FAIR Phase-0 at upgraded GSI facilties
2023 concrete construction completed
2024 start of accelerator installation
2027 first experiments with S18 beam
2028 start of operation with SIS100

GSI facilities continue operation

SIS100 primary beams:

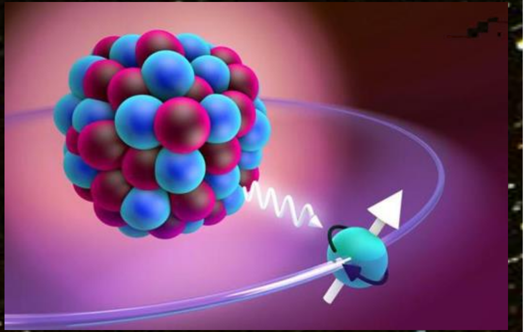
- 10^9/s Au up 11 GeV/u
- 10^9/s C, Ca, … upto 14 GeV/u
- 10^{11}/s p up to 29 GeV/u

FAIR Start of installations

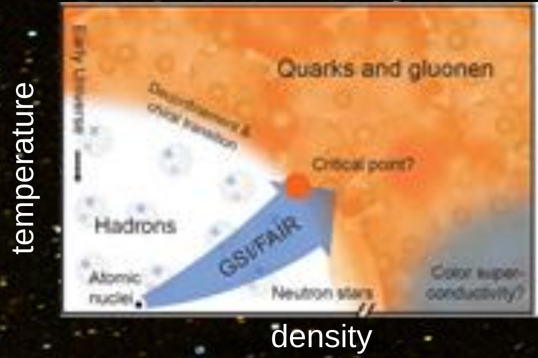
SIS100 dipoles

SIS100 power supplies

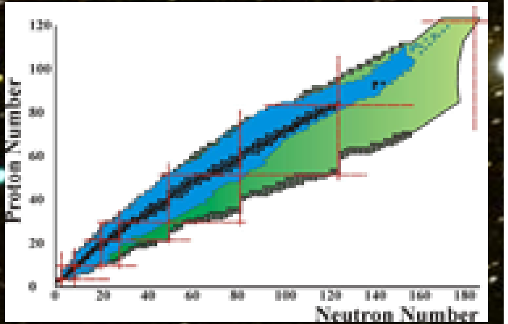
cryo plant



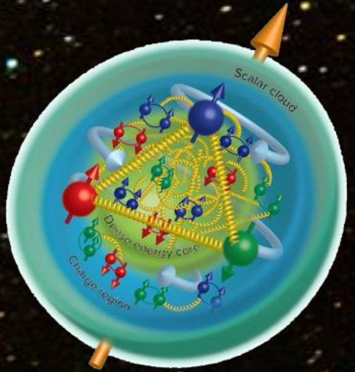
- Precision tests of QED
- Cosmic ray simulator for irradiation studies
- Materials under high pressure



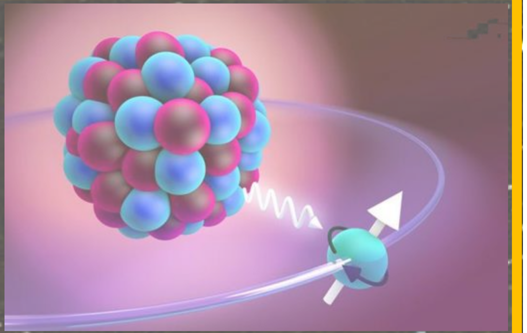
- QCD matter at high baryon densities
- Phase transition and critical point
- Particles in dense medium



- Nucleosynthesis of heavy elements
- Structure of exotic nuclei (e.g. hyper nuclei)
- Neutron rich matter equation of state



- Gluonic excitations: Hybrids, glueballs
- Precision spectroscopy of charmonium states
- Time-like form factors, nucleon structure



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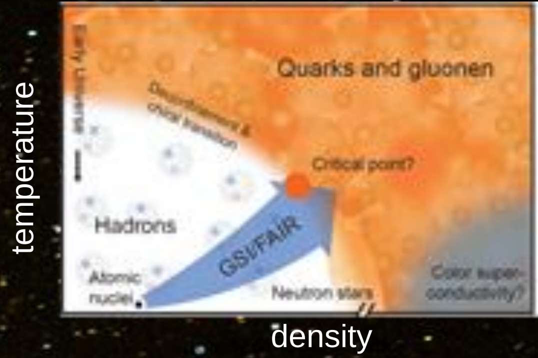

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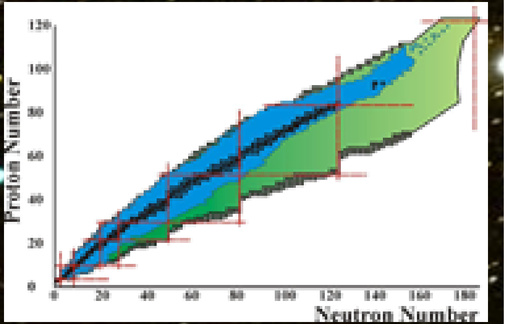

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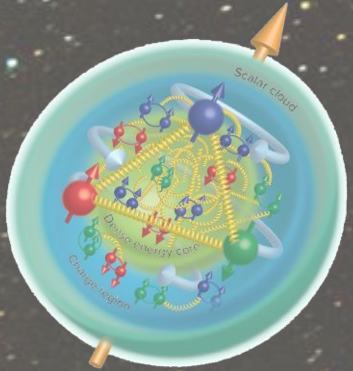

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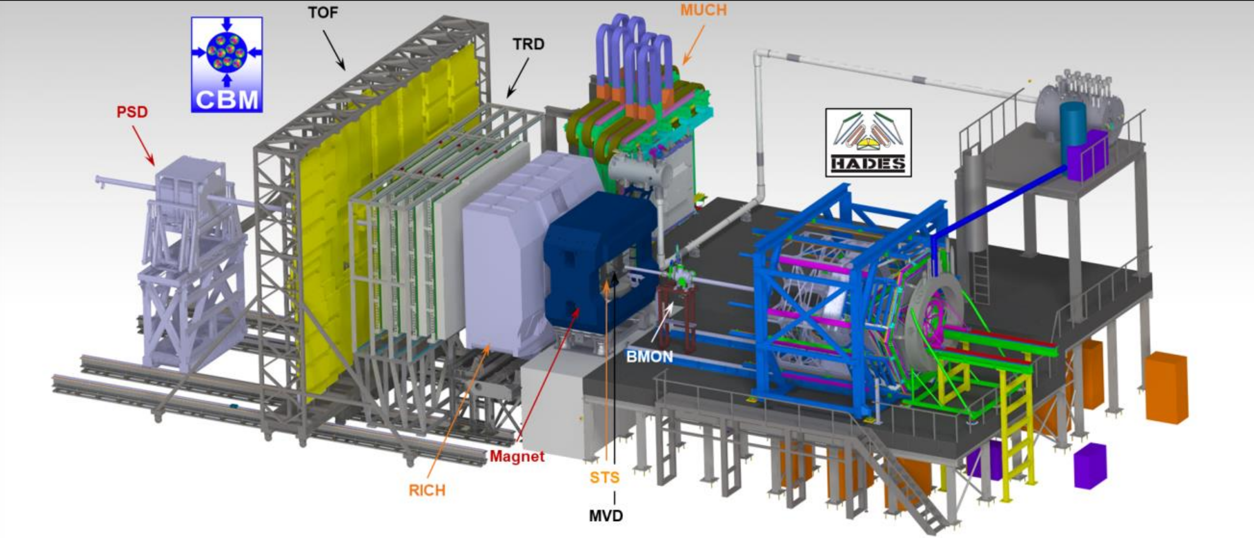
CBM/HADES @ FAIR

CBM

- Fixed target experiment tracking acceptance
  $1.5° < \Theta_{lab} < 25°$
- 2 interchangeable setups for electron and muon detection
- Peak interaction rate : 10 MHz (Au+Au) (300 kHz with MVD)
- Free-streaming, self-triggered DAQ system
- Online event reconstruction and selection
- Fast and radiation hard detectors

HADES

- complementary acceptance

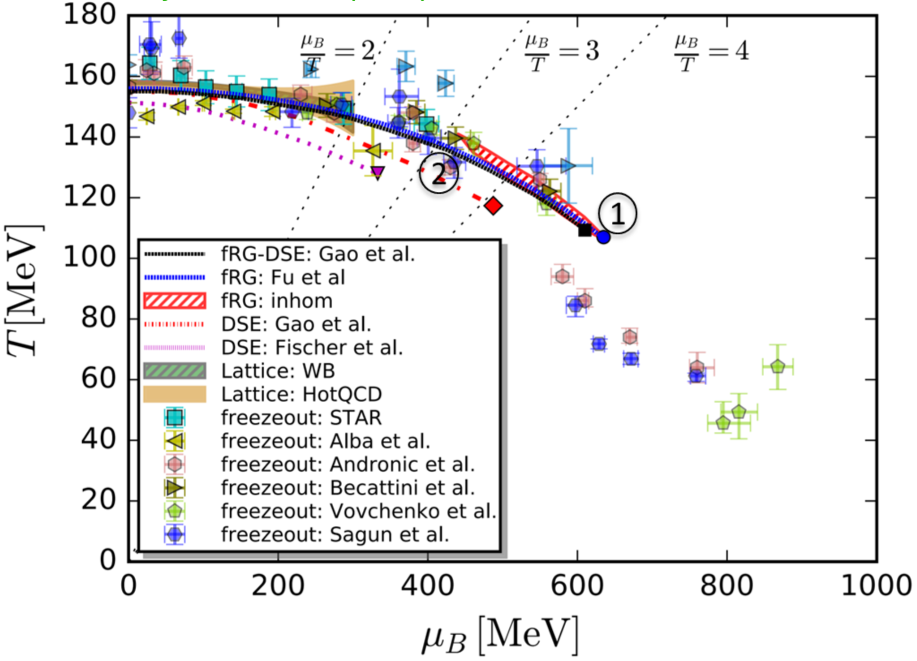


CBM Day-1 configuration (2028): rate capability 100 kHz Au+Au reactions with streaming (triggerless) readout of MVD, STS, RICH, MUCH, TRD, TOF, and PSD; HADES continues at SIS18

CBM – Scientific goal

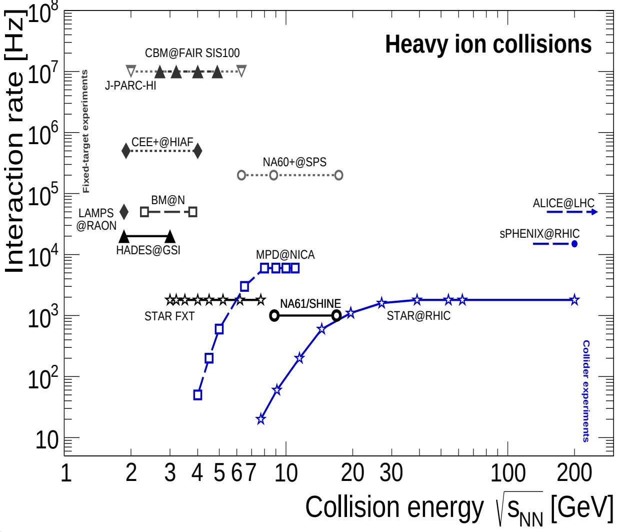
Location of chiral cross over

W. Fu, J. Pawlowski, F. Rennecke, Phys.Rev.D 101 (2020) 5, 054032, arXiv:1909.02991



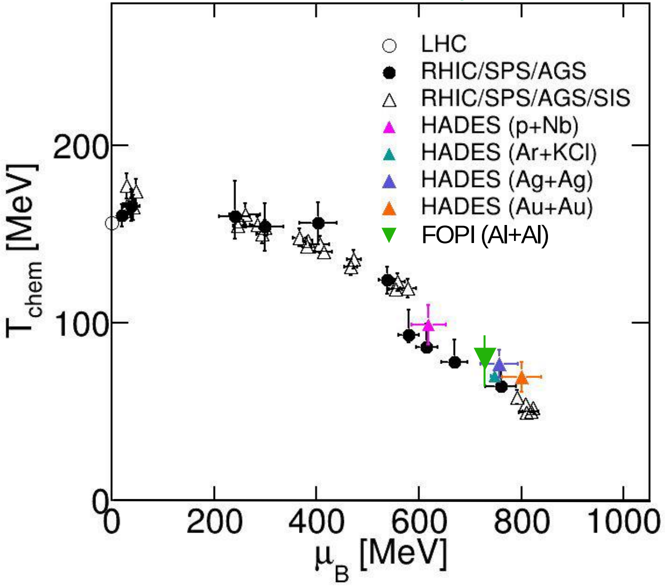
Mission:
Systematically explore QCD matter at large baryon densities with high accuracy and rare probes.

T. Galatyuk, https://github.com/tgalatyuk/interaction_rate_facilities, 2022



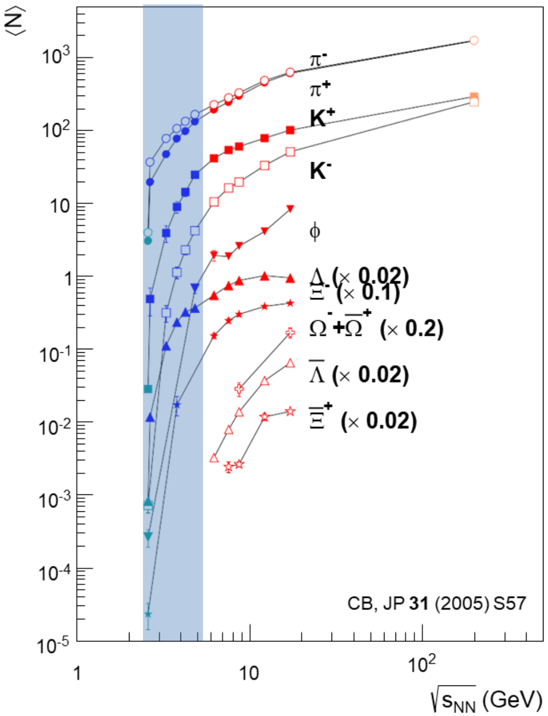
Strangeness production at FAIR

M. Kohls, HADES QM 2023



Chemical freeze-out data are fairly well described by Statistical Hadronization Model

Strangeness production central Au + Au collisions

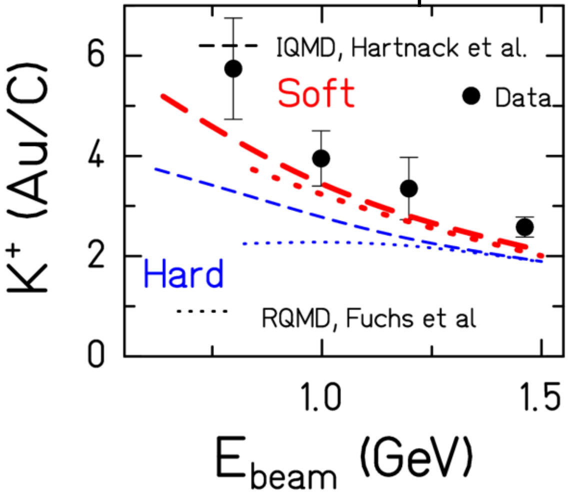


Strange and charmed particle production thresholds in pp - collisions

reaction	$\sqrt{s}$ (GeV)	T_{lab} (GeV)
$pp \rightarrow K^+\Lambda p$	2.548	1.6
$pp \rightarrow K^+K^-pp$	2.864	2.5
$pp \rightarrow K^+K^+\Xi^-p$	3.247	3.7
$pp \rightarrow K^+K^+K^+\Omega^-n$	4.092	7.0
$pp \rightarrow \Lambda\bar{\Lambda}pp$	4.108	7.1
$pp \rightarrow \Xi^-\bar{\Xi}^+pp$	4.520	9.0
$pp \rightarrow \Omega^-\bar{\Omega}^+pp$	5.222	12.7
$pp \rightarrow J/\Psi\, pp$	4.973	12.2

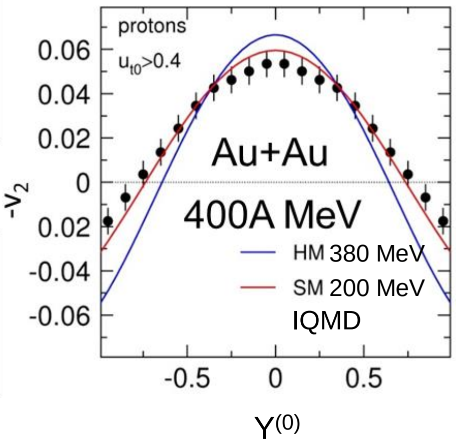
Strong sensitivity to EOS

sub-threshold kaon production



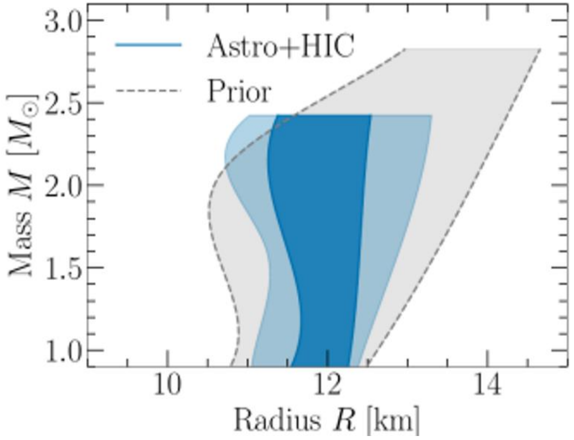
C.Sturm et al. (KaoS), PRL 86 (2001) 39,
C. Hartnack et al., PRL 96 (2006) 012302
C. Fuchs et al., PRL 86 (2001) 1974

elliptic flow



FOPI, Nucl. Phys. A 876 (2012) 1

S. Huth et al., Nature 606 (2022) 276



Multistep production in dense matter
(formation of nucleon resonances)
=> soft EOS (K ~ 200 MeV)

Pressure gradients

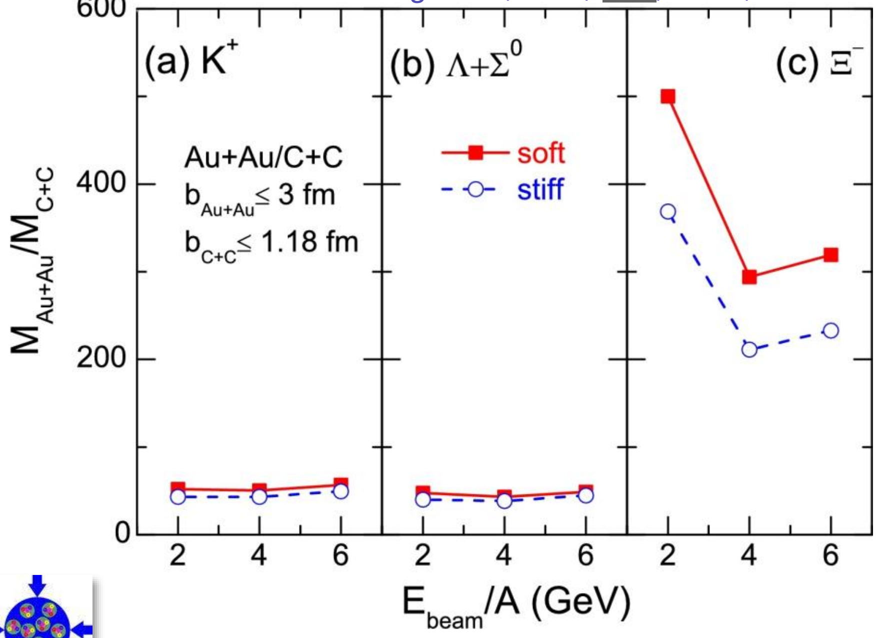
=> soft EOS (K ~ 200 MeV)

Astrophysical + HIC data
(SIS18+AGS) complementary
Higher density HIC data needed

Equation of state of nuclear matter
Observables at high density

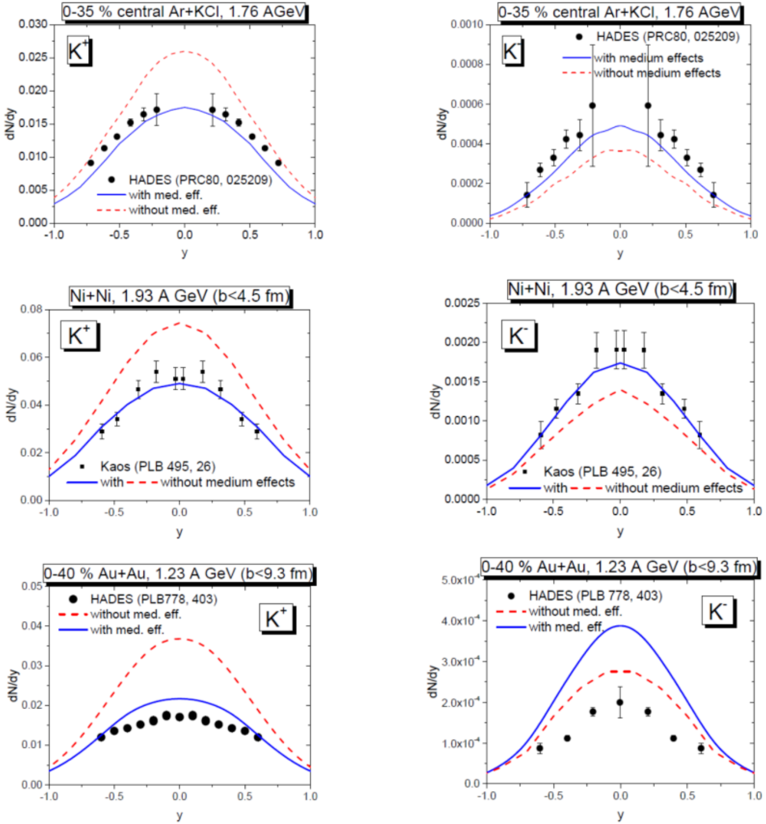
- precise measurement of
  collective flows of bulk observables
- **clusterizsation (cf. talk of E. Bratkovskaya)**
- **subthreshold particle production**
  - transport model calculations using a hadron cascade version of AMPT
  - particles like K^+, $\Lambda+\Sigma^0$ and Ξ^- are mainly produced in the high density region
  - however, one needs also to pin down the symmetry energy => K^0/K^+ ratio?

G.-C. Yong et al., PLB, 820, 2021, 136521



Kaons in dense medium

- NK$^+$ interaction
  - slightly repulsive in dense nuclear medium
  - no broadening of spectral function predicted
- NK$^-$ interaction
  - complicated due to presence of resonances
  - need coupled channels treatment (e.g. chiral effective field theory)
  - many experimental studies using K$^-$ beams
  - NK$^-$ interaction attractive at finite (ground state) densities, but strength of the potential is unclear at high densities
  - shift and broadening of spectral function as a function of momentum
  - strong absorption in medium
- Depth of NK$^-$ potential of importance
  - neutron stars



T. Song et al., (PHSD) Phys. Rev. C 103, 044901 (2021)

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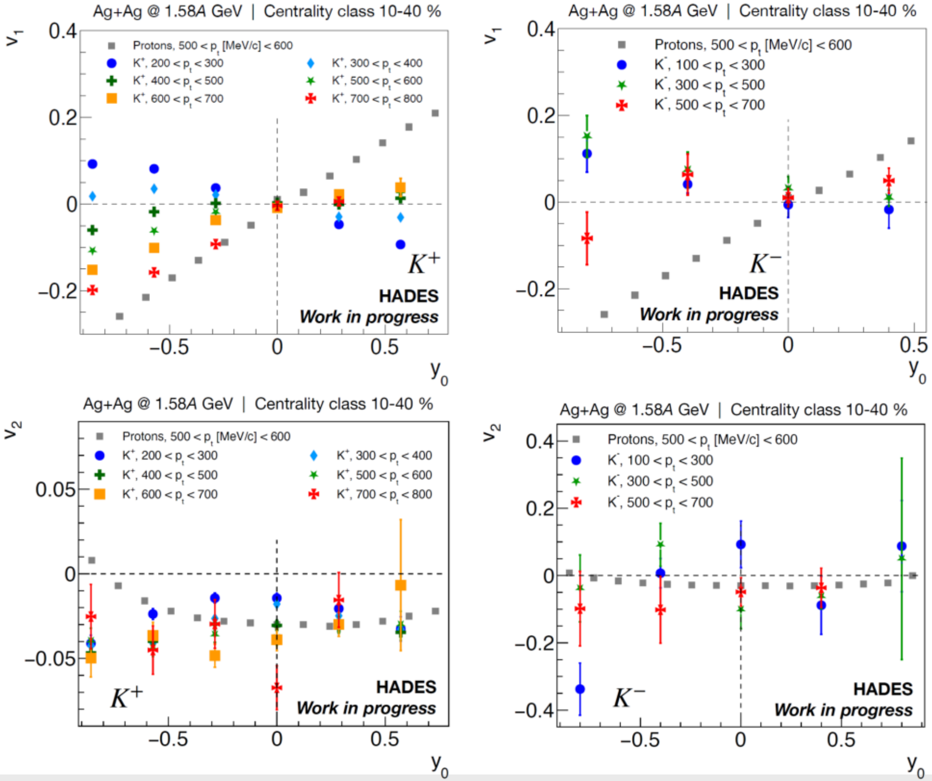
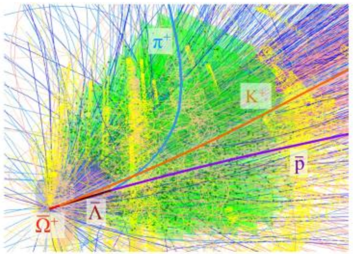
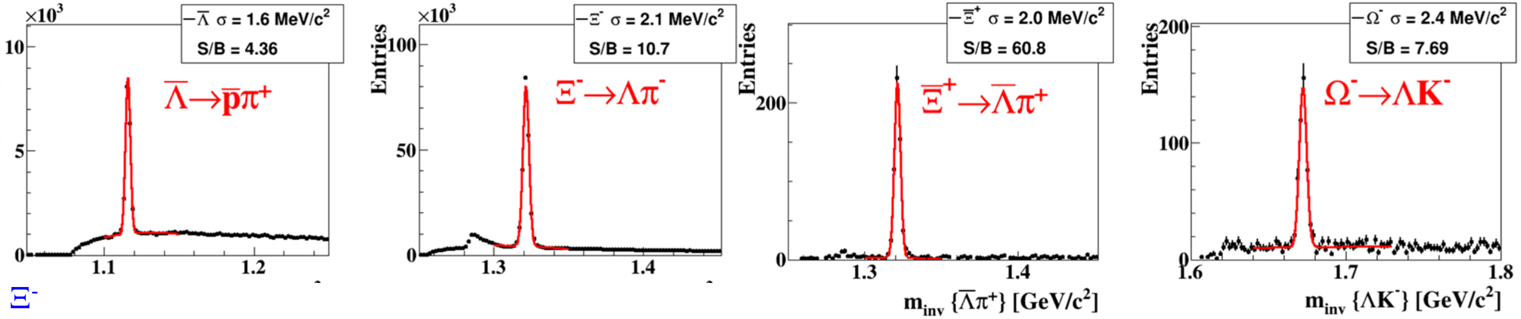
HADES, Kaon flow, Talk Jan Orlinski

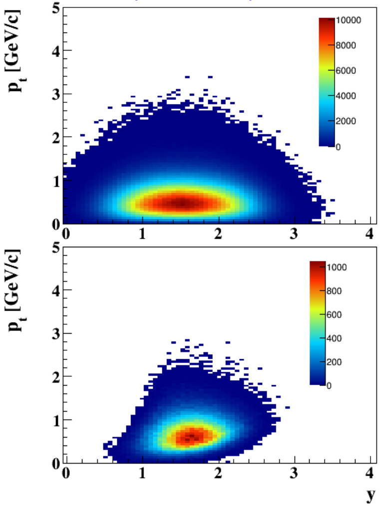


Production yields of strange hadrons





Au + Au, central, 10AGeV, Ξ^-



Particle (mass MeV/c²)	Multi-plicity 6 AGeV	Multi-plicity 10 AGeV	decay mode	BR	ε (%)
Λ (1115)	$4.6 \cdot 10^{-4}$	0.034	$p\pi^+$	0.64	11
Ξ^- (1321)	0.054	0.222	$\Lambda\pi^-$	1	6
Ξ^+ (1321)	$3.0 \cdot 10^{-5}$	$5.4 \cdot 10^{-4}$	$\Lambda\pi^+$	1	3.3
Ω^- (1672)	$5.8 \cdot 10^{-4}$	$5.6 \cdot 10^{-3}$	ΛK^-	0.68	5
Ω^+ (1672)	-	$7 \cdot 10^{-5}$	ΛK^+	0.68	3

Improvements by Machine Learning under investigation.

Statistics estimation at R_{int}=0.1 MHz for Ω^- at T=10 AGeV

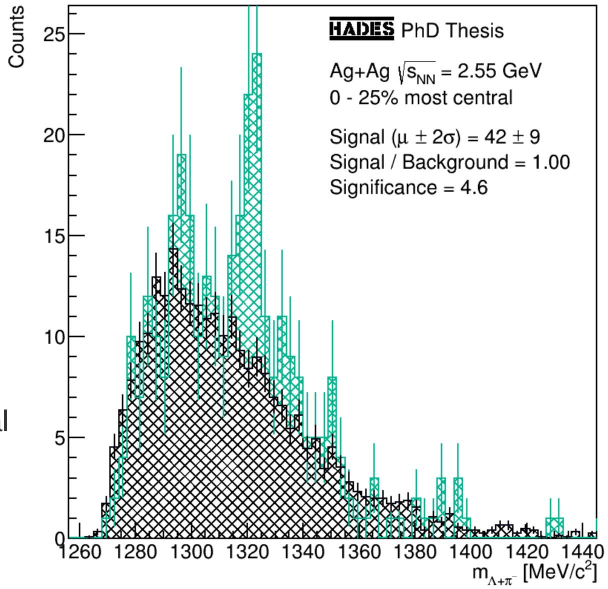
Signal counts per week:

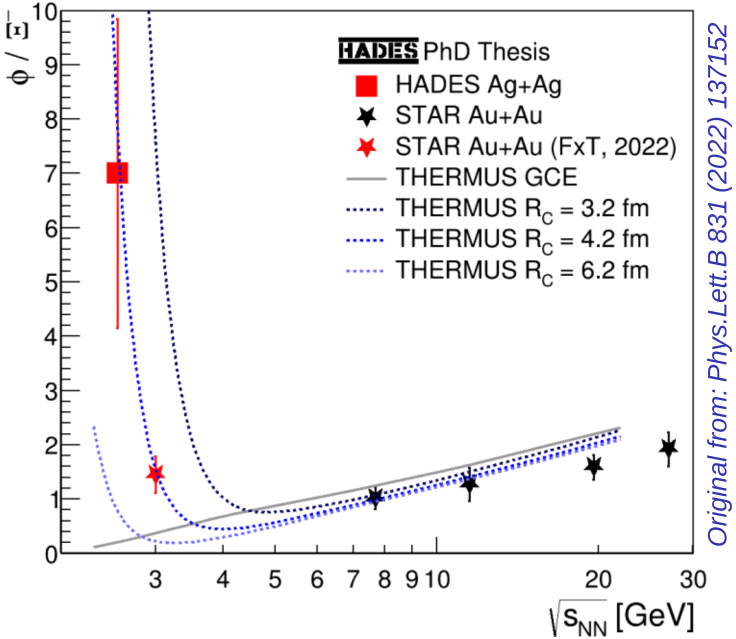
$$S_w = R_{av} * \varepsilon_{duty} * P_{prod} * f_{mb/cen} * BR * \varepsilon_{reco} * \Delta T$$
$$= 1\ 10^5 * 0.7 * 5\ 10^{-3} * 0.25 * 0.68 * 0.05 * 6\ 10^5$$
$$= 1.800.000$$

Talk I. Vasieliev

Ξ^- production in Ag+Ag @ $\sqrt{s}$ = 2.55 GeV

- Over four weeks, HADES collected 14 billion central Ag+Ag events @ $\sqrt{s}$ = 2.55 GeV
- Ξ^- hyperons detected via the decay chain: $\Xi^- \rightarrow \Lambda\pi^- \rightarrow p\,\pi^-\,\pi^-$
  - excellent background suppression by using artificial neural networks
- significance slightly below 5σ, yet clear signal above background
- first measurement of double strangeness at this energy
- Canonically extended SHM model predicts strong dependence of canonical radius R_C and Φ/Ξ^- ratio



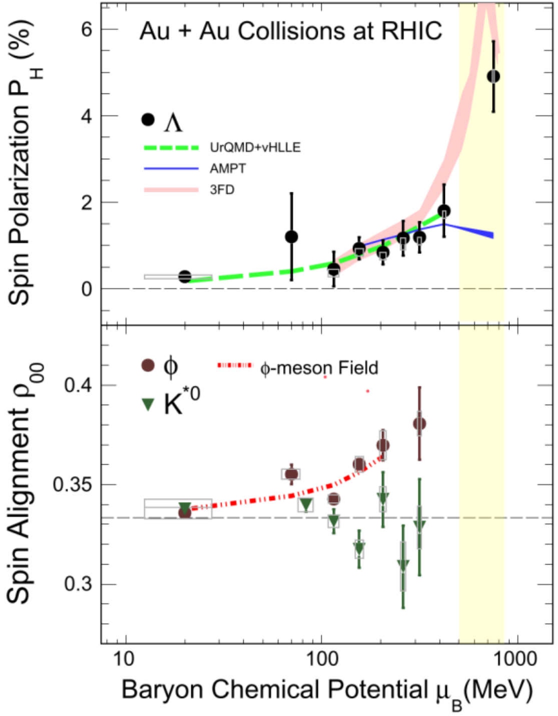


Talk of Simon Spies

Poster by Marvin Kohls "Systematics of Hidden and Open Strangeness Production in Few GeV HICs"

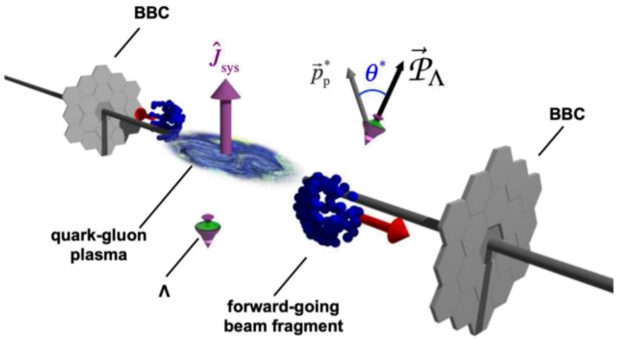
Global spin polarization / alignment / vorticity

arXiv:2209.05009v2

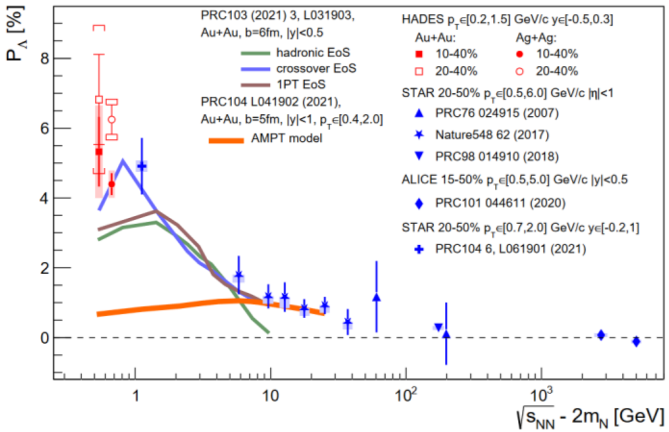


Observables pioneered by STAR

STAR, Nature 548 (2017) 62,
PRC 104 (2021) 061901,
arXiv: 2204.02302



HADES Phys.Lett. B 835 (2022) 137506, arXiv:2207.05160



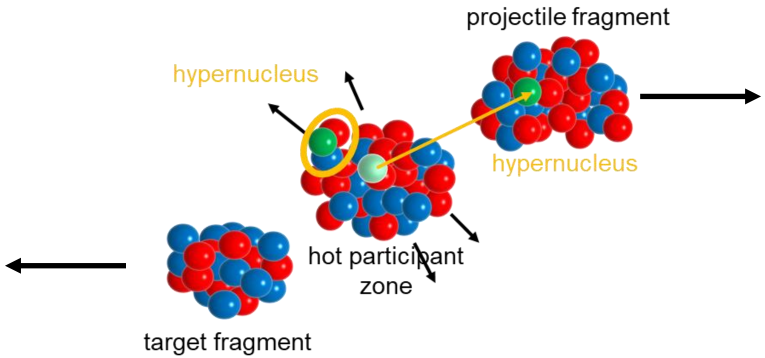
New sensitivities:

- thermal vorticity
- meson fields

Large data sets needed

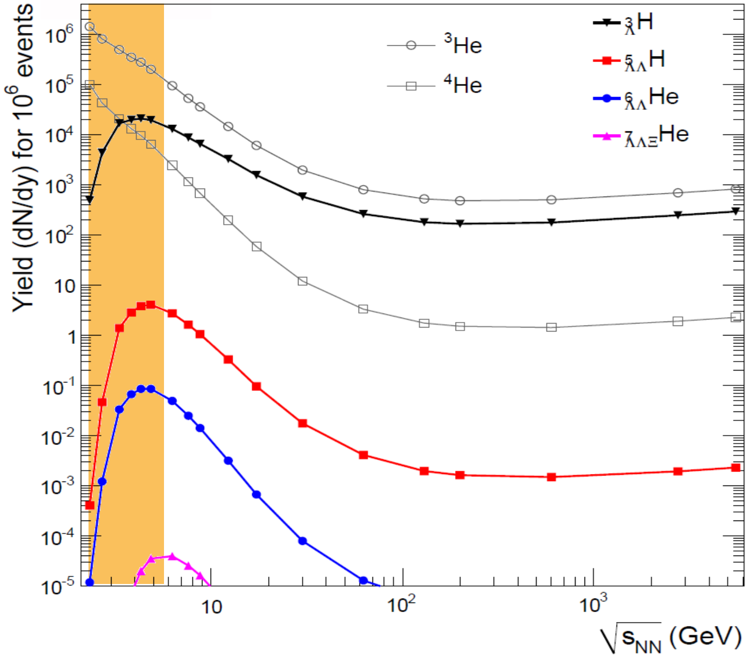
e.g. mapping of the excitation function for $\bar{\Lambda}$ requires $\geq 10^{13}$ events.

Hypernuclei production in Heavy Ion Collisions



At SIS/FAIR energies

- production of hyperons observed
- multiple production mechanisms
- coalescence hyperons with projectile/target fragments may lead to creation of heavy/exotic hypernuclei
- thermal models predict maximum of hypernuclei production at FAIR energies

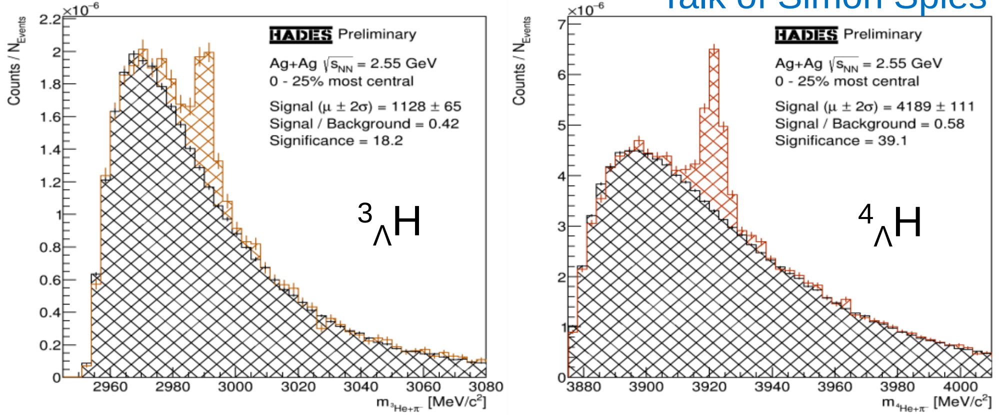


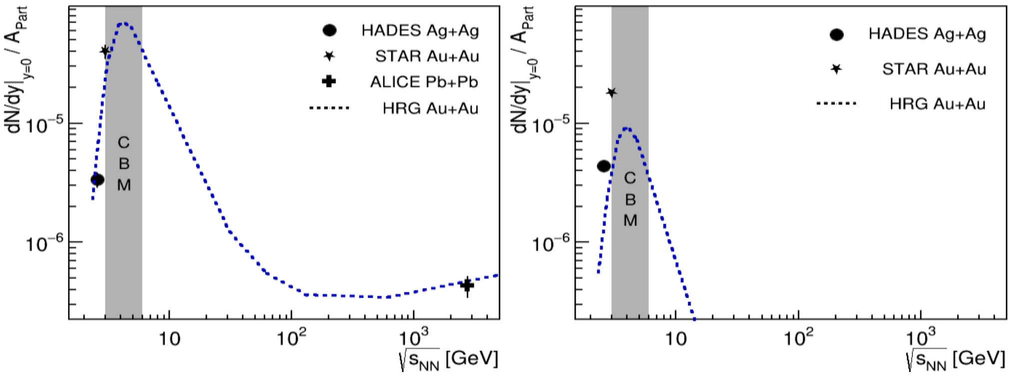
Hypernuclei at FAIR

Talk of Simon Spies

- Λ as a probe for nuclear structure
- Neutron stars: hyperon puzzle
  Y energetically favorable at 2-3 ρ_0,
  but softening of EOS leads to
  $M_{allowed} < M_{observed}$
- Hyperon interactions relevant for EOS at high densities
  ΛN, Λ Λ , ΛNN
- Hypernuclei known
  - ~40 Λ-nuclei (ΛN attractive)
  - few ΛΛ-nuclei (weak attraction)
  - few Ξ-nuclei (ΞN attractive)

HADES Ag+Ag@√s = 2.55 GeV:





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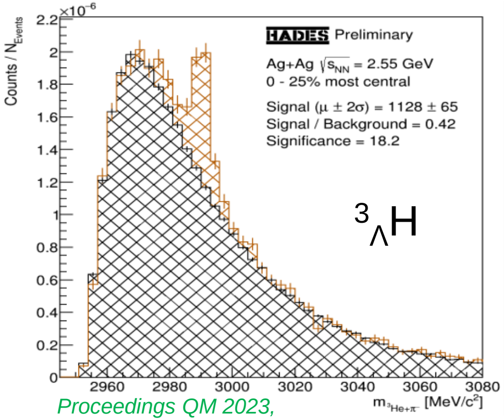
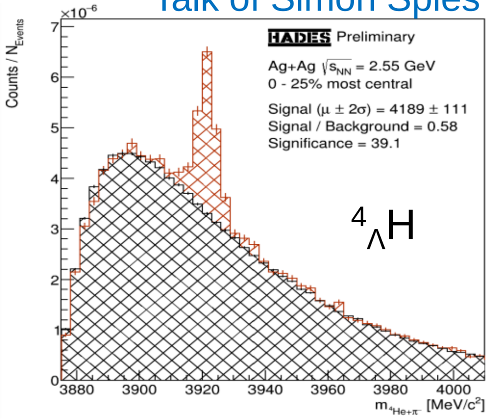
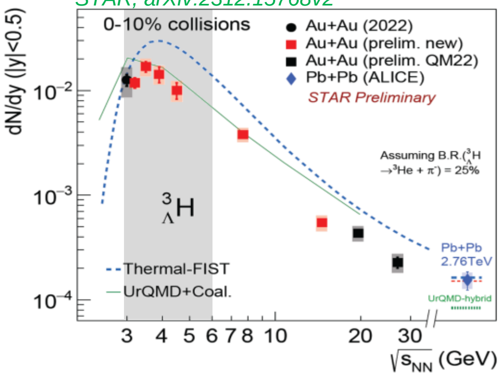
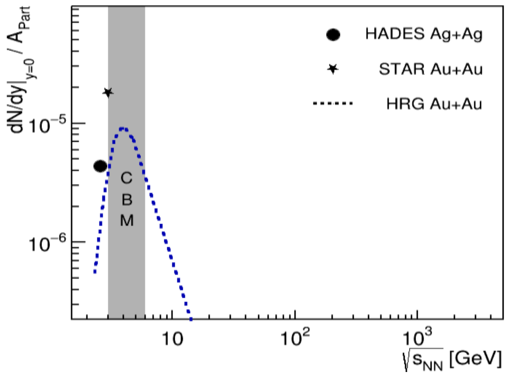




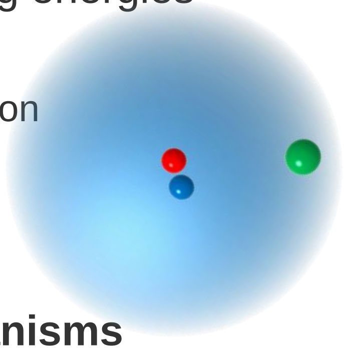
Proceedings QM 2023,
STAR, arXiv:2312.15768v2

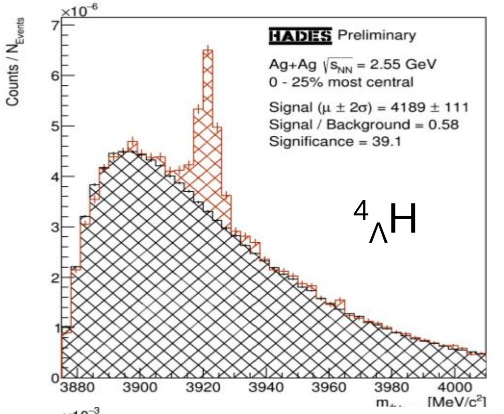


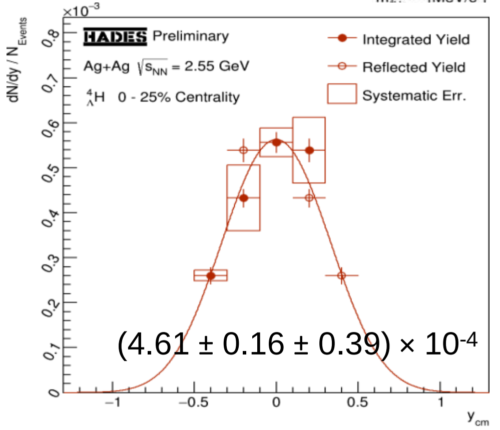


Hypernuclei at FAIR

- lifetimes and binding energies
- characteristics
  - size and deformation
  - clustering
  - excitations
  - super-halos
- **production mechanisms**
  - understanding clustering phenomena
  - hypernuclei produced in interactions of hyperons with target/projectile like spectators
  - pion induced reactions







HADES Ag+Ag@√s = 2.55 GeV:

- multi-differential analysis

Talk of Simon Spies

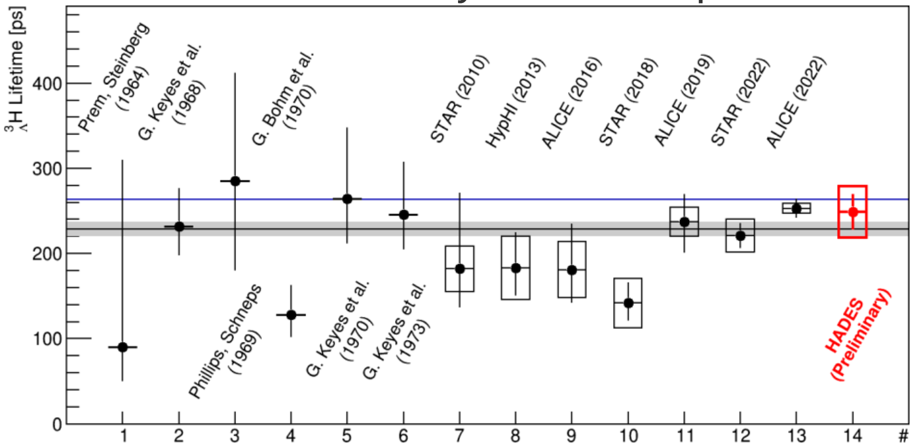
Hypertriton lifetime

- **lifetimes and binding energies**
- characteristics
- production mechanisms

Talk of Simon Spies

HADES Ag+Ag@√s = 2.55 GeV:

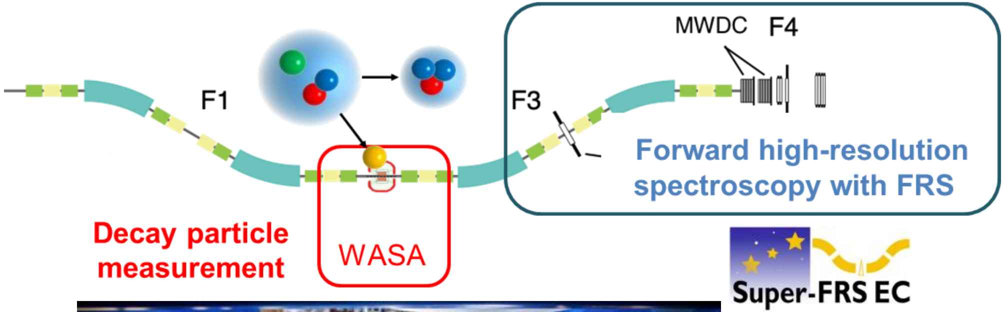
- Lifetime of (249 ± 21 ± 30) ps compatible with free Λ lifetime measured
- Extensive uncertainty evaluation performed

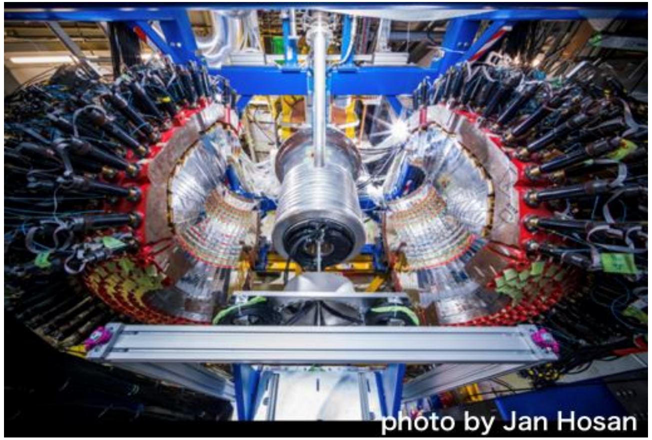


Hypertriton lifetime

- is expected to have lifetime within few % of the free Λ lifetime τ_Λ

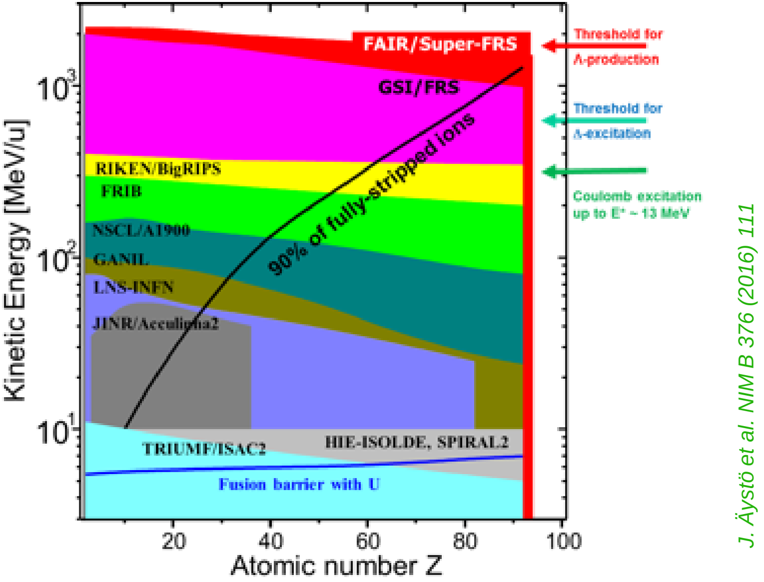
Exotic hypernuclei at FAIR





WASA at (Super)FRS

- high precision spectroscopy of heavy decay remanant
- **stable and radioactive beams** possible (proton- and neutron rich)



Exotic hypernuclei at R3B
(Reactions with Relativistic Radioactive Beams)

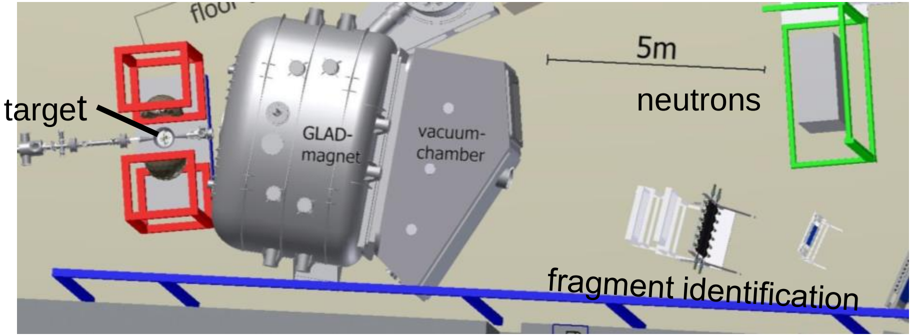
Radioactive nuclei produced and identified in (Super) Fragment Separator

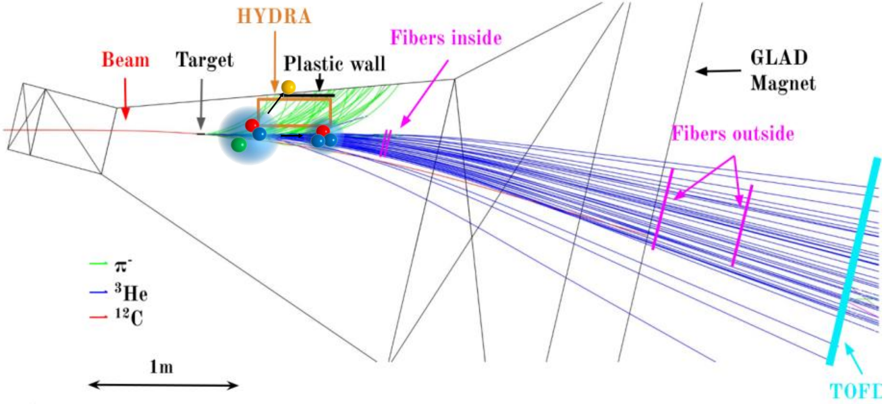
π⁻ tracker for R3B

- high resolution
- neutron detection

Challenge

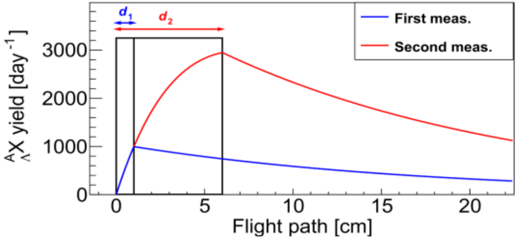
- non-homogenity of the dipole field



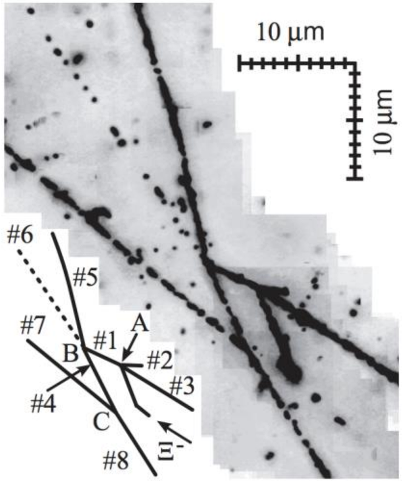


1st experiment @ FAIR

- measurement of hypertriton's interaction cross section



ΛΛ hypernuclei in CBM

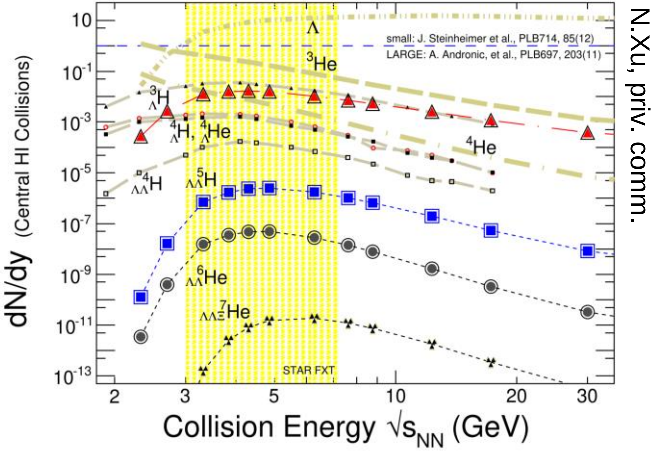


$$^{12}\mathrm{C} + \Xi^- \rightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$
$$\hookrightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^-$$

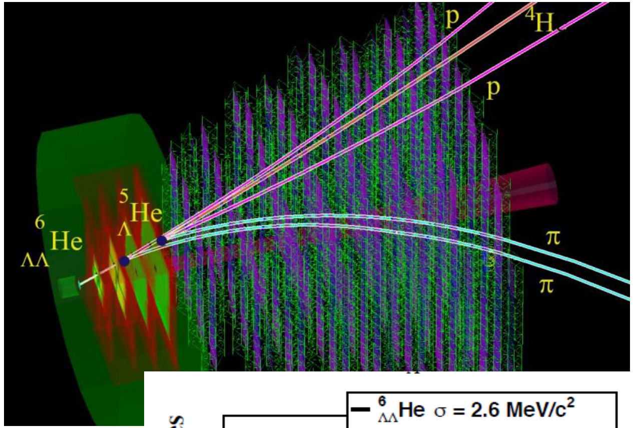
The S=-2 Nagara event

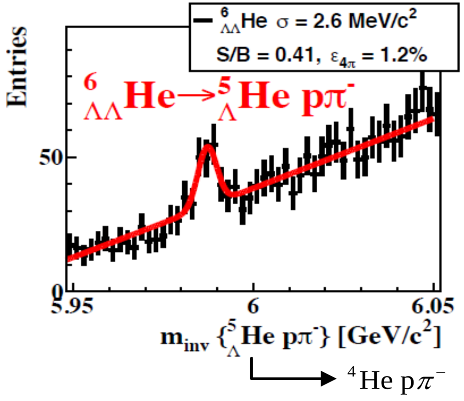
Takahashi et al., PRL (2001)

Model predictions for Au+Au



Decay topology





$^{6}_{\Lambda\Lambda}$He - runtime estimate at peak interaction rate of 10 MHz

Inspected events per week: $2 \cdot 10^{12}$

Signal counts per week:

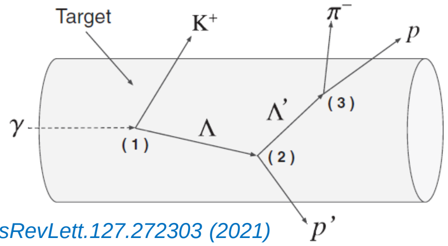
$S_w = R_{peak} * f_{av} * \varepsilon_{duty} * P_{prod} * f_{mb/cen} * BR * \varepsilon_{reco} * \Delta T = 60$

Talk of Iouri Vasiliev

ΛN interaction

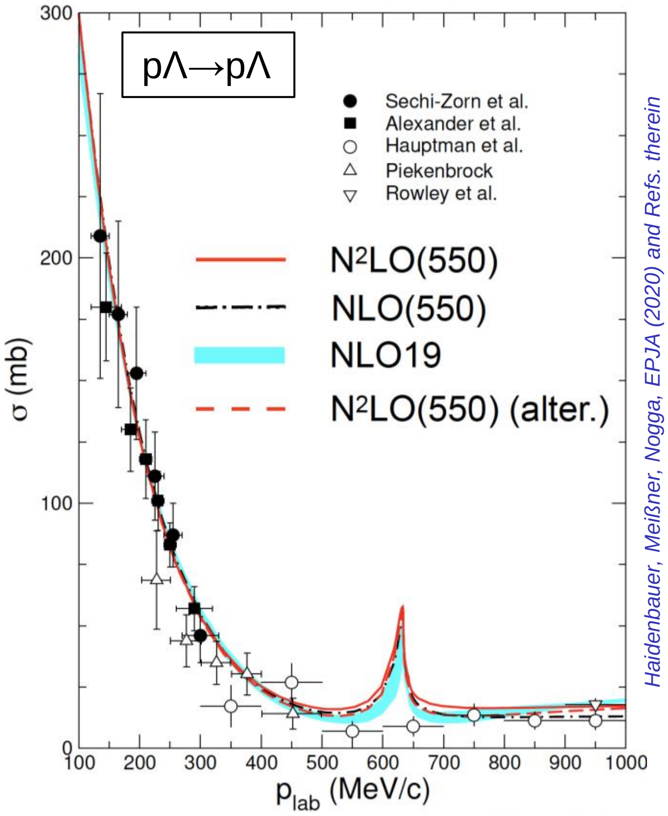
Scattering data with hyperon beam

ΛN < 50 data points (poor beam quality, short lifetime, extrapolation down to low momenta)



CLAS PhysRevLett.127.272303 (2021)

NN > 5000 data points below 350 MeV



Haidenbauer, Meißner, Nogga, EPJA (2020) and Refs. therein

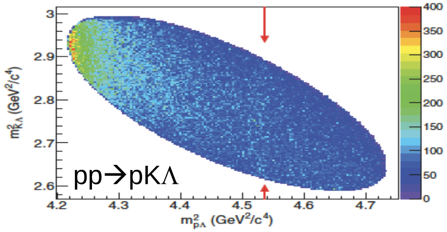
Strangeness
in pp/pA collisions at SIS100

Proton beams at SIS100

- 10^{11} to 10^{12} protons per (10s) spill upto 30 GeV/c

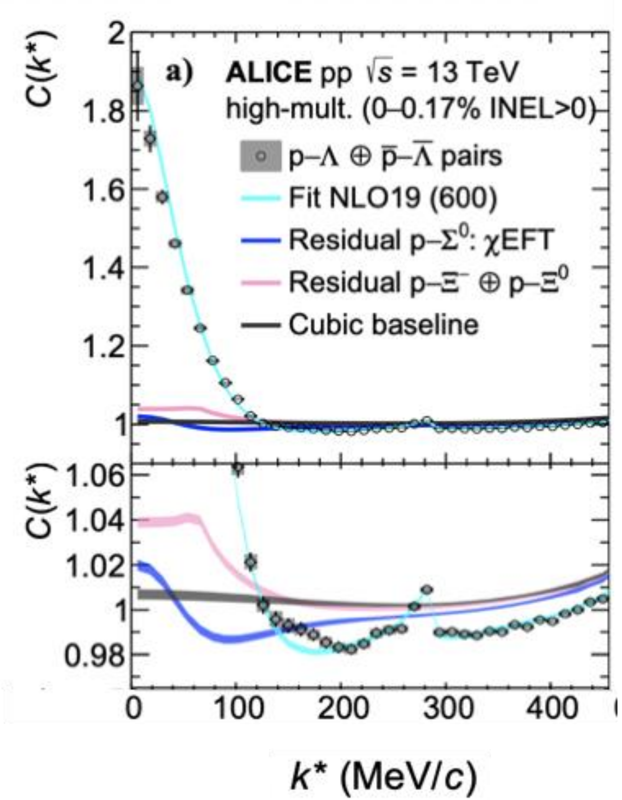
Study ΛN interaction

- Femtoscopy
  - less feed down than at LHC
- Dalitz plot analysis of exclusive final states



F. Hauenstein PRC95(2017) 034001

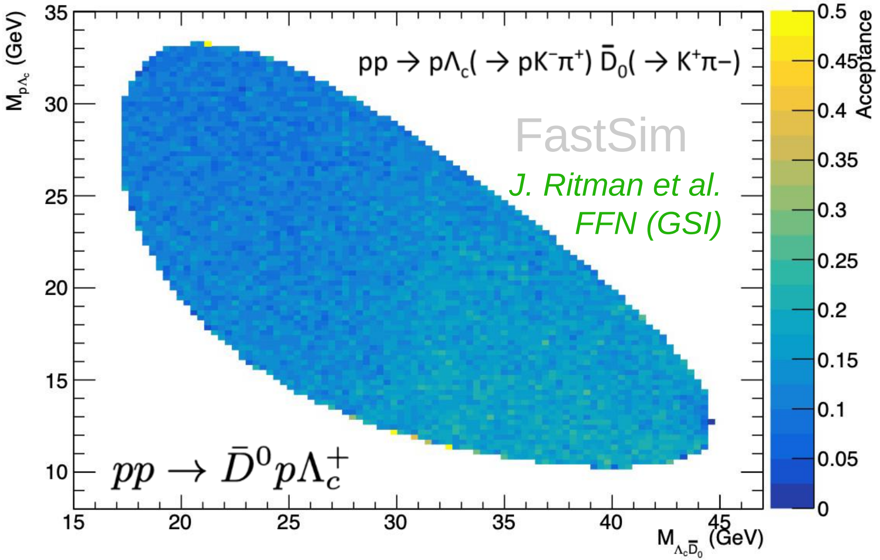
- Interesting perspective for $\Sigma^+\Sigma^+$ interaction
  - via pp → $\overline{K}^0\overline{K}^0\,\Sigma^+\Sigma^+$



ALICE Phys.Lett.B 833 (2022) 137272

Charm production in pp/pA collisions at SIS100

- SIS100 energies allow for charm production channels
- SU(4) estimates for exclusive charm hyperon production up to 1 μb @ SIS100
- all final state particles reconstructed
  - good phase space acceptance of the primary particles with CBM
- detailed studies D-p and Λ_c-p interactions possible with femtoscopy



Expected reconstructed exclusive events / Day @ 30 GeV/*c*, σ = 1 μb	
1 MHz	$2.7\cdot10^4$
10 MHz ?	$2.7\cdot10^5$

Charm production
in pp/pA collisions at SIS100

J/ψ production

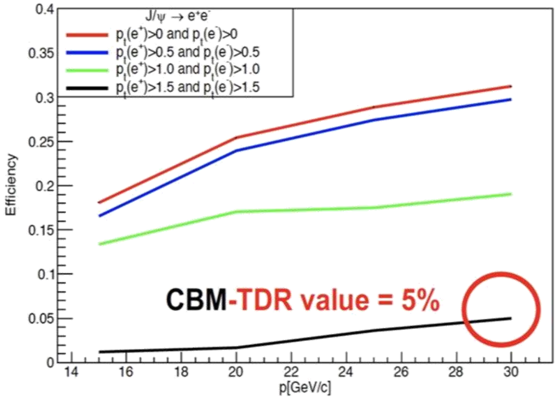
- Cross section ≈ 1 nb at 30 GeV/c ($\sqrt{s}$=7.5 GeV)
- Large and uniform reco eff. 5-30%
- Strong background suppression (Kinematic-fit)

Scientific questions

- Influence of internal charm of proton on cross section close to threshold?
- J/ψ-N interaction with multiple gluon exchange with proton
  - Forward (t=0) J/ψ dσ/dt related to J/ψ–N scattering amplitude, and nucleon mass via trace anomaly
  - J/ψ-N interaction related to pentaquark searches (LHCb pentaquark states not observed by GLUEX)
  - J/ψ in-medium characteristics
- pp-reactions to explain effects in pA/AA-reactions

Signal	Cross Section [μb]
$pp \to ppJ/\psi(\to ee)$	10^{-3} (×0.06 BR)

Reco Efficiency pCBM: $pp \to ppJ/\psi$



Expected reconstructed exclusive events / Day @ 30 GeV/c, σ = 10^{-3} μb	
1 MHz	$1.6 \cdot 10^3$
10 MHz	$1.6 \cdot 10^4$

Summary and outlook

High intensity and high data rate capabilities of CBM opens up a wealth of different physics opportunities for strangeness and charm research

- equation of state of dense matter
- in-medium characteristics of strangeness
- interactions in particular multi-body interactions
- hypernuclei
- strangeness and charm in pp and pA collisions
- **strangeness in pion induced reactions@SIS18**

Support from Theory is indispensable

2027 Start of experiments at
Super-FRS with SIS18 beams

2028 Start of experiments with SIS100

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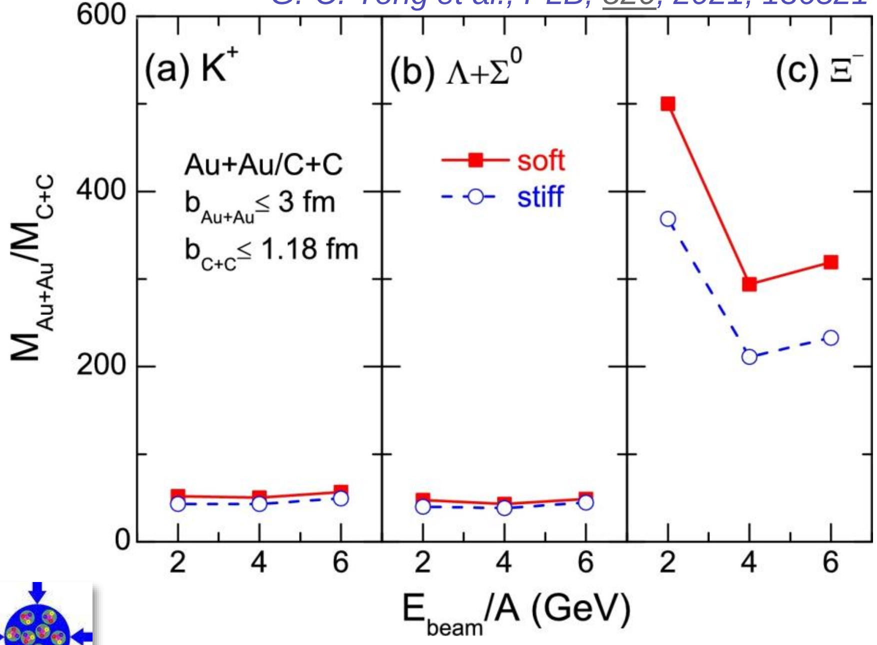
Exploring Strangeness and Heavy Quarks at FAIR

Yvonne Leifels

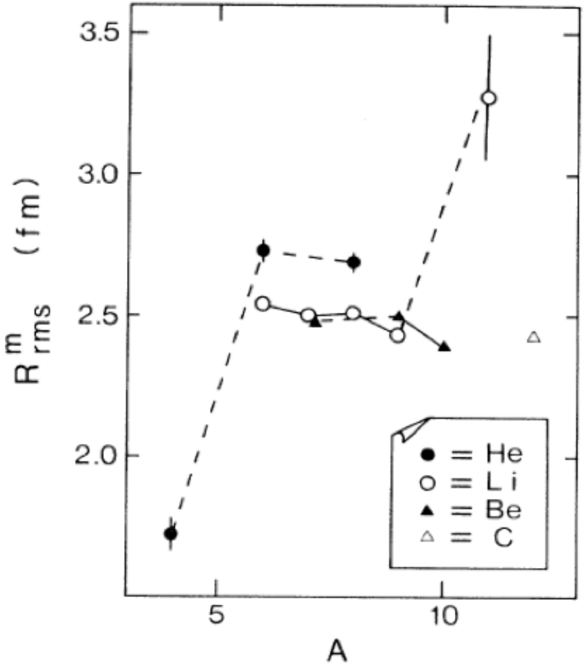
Equation of state of nuclear matter
Observables at high density

- precise measurement of **collective flows of bulk observables**
- **clusterizsation (cf. talk of E. Bratkovskaya)**
- **subthreshold particle production**
  - transport model calculations using a hadron cascade version of AMPT
  - particles like K^+, $\Lambda+\Sigma^0$ and Ξ^- are mainly produced in the high density region
  - ratio of Ξ^- from heavy and light systems show strongest sensitivity
  - observable easily accessible by CBM
  - transition to neutron rich matter

G.-C. Yong et al., PLB, 820, 2021, 136521



Light halo nuclei



I. Tanihata et al., PRL (1985)

S. Acharya et al, *Measurement of the Lifetime and Λ Separation Energy of ${}_{3}^{\Lambda}H$, Physical Review Letters (2023).*

[DOI: 10.1103/PhysRevLett.131.102302](https://doi.org/10.1103/PhysRevLett.131.102302).